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A New Deep Space Network for the Next Century

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Abstract

NASA's Deep Space Network (DSN) is responsible for providing communications, tracking, and science services to most of the world's spacecraft that travel beyond low Earth orbit, Changes occurring to the DSN'S customers arc forcing the DSN to change substantially as wc]] - in capability, capacity, and efficiency. Spacecraft tracked by the DSN arc becoming smaller and cheaper, while still requiring significant science returns, This places increased demands on the DSN to adopt ncw technologies and improve the quality of the services it provides. Some of these technologies include beam waveguide antennas, Ka-band communications, cooled HEMT amplifiers, adaptive microwave optics, new error correcting codes, and ultra-stable ionic frequency standards. At the same time, budget constraints from NASA have resulted in a significant decrease in funds spent on mission operations - including the DSN. This means the DSN must adopt all this new technology while halving the average cost for each tracking hour it provides. The DSN will achieve this increase in efficiency by a complete reengineering of its operations processes - redefining operat ions jobs and taking advantage of advances in information systems technology and automation. This paper describes both the new technologies and ncw operations concepts that, together, will allow the DSN to continue its leadership in deep space communications and tracking.

1. The DSN'S Customers

NASA's Deep Space Network (DSN) is the responsibility of the Ground Networks Division of NASA's Office of Space Communications. The DSN is managed for NASA by the Jet Propulsion laboratory (JPL) in Pasadena, California.

The DSN is responsible for providing communications, tracking, and science services to most of the world's spacecraft that travel beyond low Earth orbit. The DSN also provides services to a large number of Earth orbit ing spacecraft, including low Earth orbiters (LEOs), highly elliptical Earth orbiters (HEOs), and geostationary Earth orbiters (GEOs). The DSN provides these services either to supplement NASA's Tracking and Data Relay Satellites (TDRSS) during periods of outage, or if the customer cannot afford to carry the communications systems required to operate through TDRSS.

It is the customers that drive the DSN to change with time. It has been that way since the DSN was established in 1963. Each new deep space missi on required ncw capabilities from the DSN and the DSN responded by building larger antennas, new detectors for higher frequency communications, lower noise receivers, more precise clocks, etc. Each subsequent generation of deep space mission has resulted in orders of magnitude increases in the DSN's performance.

Figure 1 shows the evolution of one useful metric with time. This is the telemetry (downlink data) capability of deep space communications using the DSN. The data in the Figure has been normalized so that the target spacecraft is always at the same distance (nominal Jupiter distance.) In this way, wc can track i mprovements in the communication system without having to account for the degradation of the spacecraft signal due to distance. The Figure includes performance improvements made in both the

DSN and on the spacecraft. In fact, it is the end-to-end system that determines the performance. Improvements in the space and ground systems are developed in coordination at JPL to achieve the best science return at the lowest cost. The Figure shows that telemetry performance has increased by nine orders of magnitude since 1963.

We have now entered an era in which the DSN's customers are still driving improvements in the ground system - but for a different reason. Rather than requiring large improvements in performance, new deep space missions are requiring large savings in cost. As NASA's overall budget decreases with time, and large projects such as the Shuttle and Space Station drive priorities, the funding left over for deep space exploration decreases even more. The era of large, expensive planetary spacecraft (such as Voyager, Magellan, and Galileo) has ended. The Cassini mission to Saturn will be the last of this breed. Future deep space missions will be substantially lower cost.

Lower cost DSN customer missions will most likely result in more capability being required from the DSN. Unfortunately, the DSN'S budget is also decreasing. The only way to keep up with the demand is through the development of new technologies that will allow the DSN to improve its performance (in telemetry and other areas as well) while, at the same time, reducing the overall mission costs to NASA.

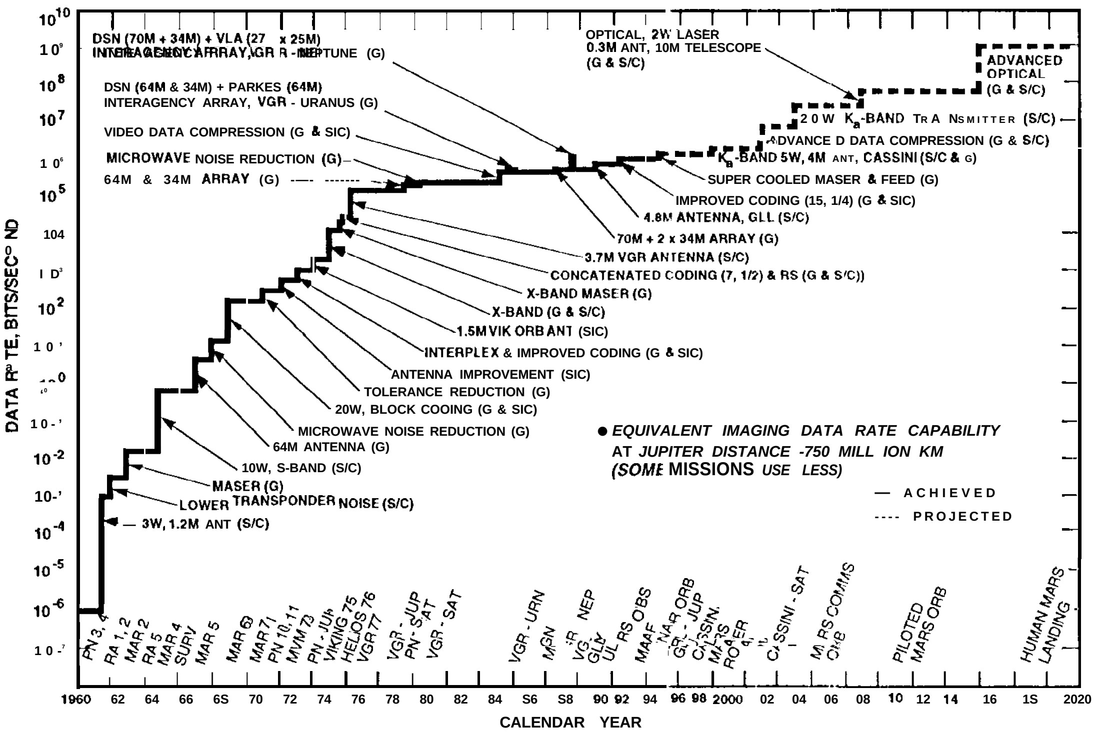

Figure 1.
History of deep space telemetry performance

Because deep space missions will be much lower cost, there will be more of them in flight at any given time. The number of DSN customer spacecraft in flight in 1994 was 16. This will grow to 40 by 1999. This will force the DSN to add the capacity required to support these simultaneous customers.

Many of these new technologies arc discussed in the following Sections. The DSN has access to these technologies because NASA has funded a DSN advanced technolog y program since the DSN began. This program has enabled the DSN to meet its past and present challenges. It is a crucial tool in meeting the future challenges as outlined in this paper.

2. Beam Waveguide Antennas

Since its beginning, the DSN has led the way in the maximizing the ratio of gain to noise (G/T) in large antennas, The DSN's 70m antennas arc among the world's largest steerable antennas used for deep space communication and tracking,

The growing number of in-flight customer spacecraft has resulted in a growing of the DSN's antenna resources. Figure 2. shows the planned antenna configuration in the DSN in the year 1999. Most of the new antennas arc 34m Beam Waveguide antennas.

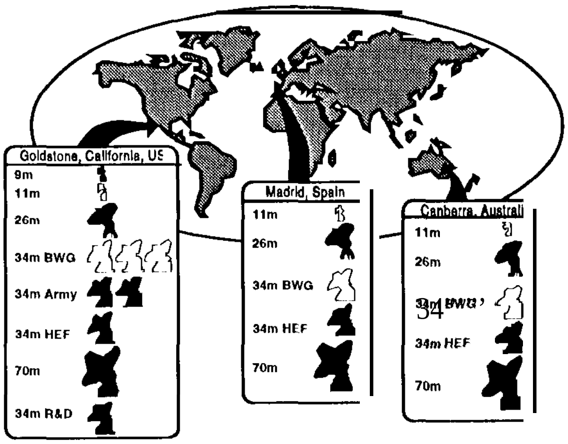

Figure 2.
DSN Antennas in 999.
White antennas are new since 1994

A beam waveguide antenna uses a series of microwave mirrors to channel energy from the surface of the dish to a focus in a controlled environment under the main structure. There is nothing new in the concept of a beam waveguide antenna. JPL's contribution has been to make the beam waveguide antenna suitable for DSN application.

The DSN beam waveguide antennas use a shaped primary and secondary reflector to increase aperture efficiency. Construction and materials selection (and the use of new low noise amplifiers - see Section 4) have resulted in optimized G/T for DSN frequencies. Further, the reflector accuracies have been fine tuned to allow operation at Ka-Band (see section 3).

The first DSN beam waveguide antenna was built at the research and development site at Goldstone, DSS13 [1]. The 34m DSS13 antenna has served as a test bed for developing antenna building techniques. Lessons learned from DSS 13 have already been used to improve the performance and lower the cost of subsequent DSN beam waveguide antennas. The first operational DSN beam waveguide antenna came on line in 1995 at Goldstone.

Figure 3. shows a cut away view of the DSS13 antenna. The advantage of the beam waveguide configuration is that very little electronics needs to be placed on the tipping structure of the antenna. Instead, the front end equipment is located under ground, in a laboratory environment. The slightly increased antenna structure cost over a cassegranian system is more than offset by the reduced cost of the front end equipment. A rotating elliptical mirror in the basement can direct microwave energy to any of several sets of front end equipment. In this way, the DSN can easily expand its capabilities in higher frequencies without adding weight to the already overcrowded cassegrainian focus areas of our conventional antennas.

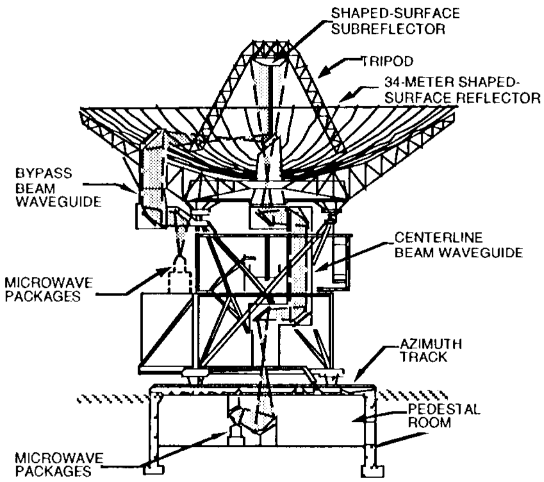

Figure 3.
The DSS13 Research and Development Antenna

One special feature of the DSS13 antenna is the bypass beam waveguide. This second waveguide can route energy over the edge of the dish. It is a prototype for possible future retrofitting of our 70m antennas.

Although there are signal degradations from the additional mirrors in the waveguide, these are offset by the environmental control of the front end equipment and the ability to cool more of the microwave components (because they do not have to tip.)

Reduced operating costs also result from the beam waveguide technology. The reduced weight on the tipping structure will mean longer bearing life. Since the front end equipment is mostly in an easily-accessible location, it will cost less and take less time to service. Also, the antenna need not be taken out of service to repair front end equipment.

3. Ka-Band

It is well known that communications performance increases like the square of the carrier frequency. For this reason, the DSN has moved steadily to higher frequency operation over the years. Today, the main frequency of the DSN is X-band (8.4 GHz.)

The next step in frequency will be to Ka-Band (32 GHz.) DSS13 was built with Ka-band in mind and it has the DSN'S first Ka-band receivers. Transmitters at Ka-band will be added in the near future.

If there were no degrading effects, then for the same size spacecraft and ground antennas, Ka-band should have about a 11.6 dB performance advantage over X-band. Unfortunately, several effects limit this advantage [2], For one, Ka-band is much more strongly effected by water vapor in the Earth's atmosphere. Antenna surface accuracy must be greater to allow efficient Ka-band operation. The narrower beam requires more accurate antenna pointing. Also, front end electronics on both the spacecraft and ground tend to be noisier at Ka-band than at X-band,

All these effects combine to give a predicted relati vc performance as shown in Figure 4. The data in this Figure come from experimental measurements performed at DSS13 together with expected improvements in the DSN research program by the year 2000. It should be noted that X-band performance is also expected to improve by 2000. Figure 4 shows the advantage of Ka-band over X-band taking this into effect,

Atmospheric losses appear at the top of the chart. There is little we can do about these short of placing the DSN antenna in orbit (this has been studied several times but is unlikely to occur in the next decade because it is not cost effective.)

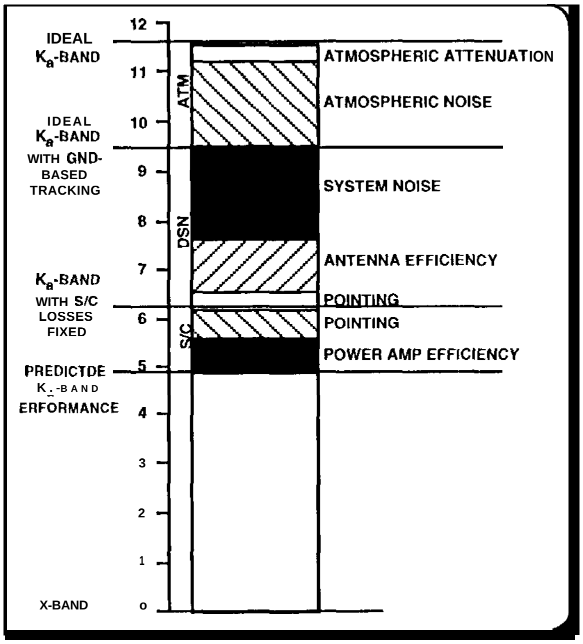

Figure 4.
Predicted Ka-band link performance Relative to X-hand for the year 2000

The next set represent DSN losses that wc arc currently working to reduce even further. These arc followed by a set of spacecraft losses. Wc arc also working to reduce these.

A similar Figure produced in 1993 showed only a 2.4 dB advantage for Ka-band. improvements since that time have included more efficient spacecraft solid state power amplifiers (S SPAS), better pointing at DSS 13 using a steerable secondary mirror, and improved DSS13 antenna efficiency.

When all of these arc taken together, the performance advantage of Ka-band over X-band is expected to be 4.9 dB by 2000. With further improvements expected in the research and development program over the next fcw years, wc expect this advantage to be grow to between 6 and 8 dB.

At the same time, wc are working to reduce the cost of adding a Ka-band capability to the DSN. The cost of adding Ka-band front ends to three 34m beam waveguide antennas has been reduced from as estimate of $30M five years ago to about $18M today. Much of this is duc to technology improvements that will be described below, in addition to operational experience gained from 1)ss13.

4. HEMT Amplifiers

W'hilt it is obviously important to maximize the efficiency and surface area of our antennas to increase their gain, it is equally important to maintain a low noise floor in the front end electronics. The overall performance of the s ystem is a strong function of G/T. For this reason, the DSN has traditional l y employed t he lowest noise technologies for its front end detection amplifiers (known in the DSN as low noise amplifiers, or LNAs.)

Currently, the best LNAs that the DSN employs arc maser amplifiers. AT X-band, these usc ruby rods that arc cooled to a physical temperat urc of 4.5 K to produce a very low systcm noise temperature of about 20 K.

A protot ypc X-band ultra low noise amplifier (ULNA) was developed for DSS13 that cools the ruby to a physical temperature of 1.6 K [3]. The ULNA achieved a record systc m noise temperat urc of 14.4 K. It is currently used as part of the Goldstone Solar System Radar to produce radar images, of planets, asteroids, and comets.

'J 'he problem with the X-band ULNA is cost. It is expensive to build and even more expensive to operate. It is cooled with superfluid helium, The cooling system is expensive and labor intensive. Onc important lesson learned from the ULNA was that there was considerable performance improvement to be had from cooling more than just the maser. The ULNA also has a cooled horn and feed - taking full advantage of the fact that, in a beam waveguide antenna, it dots not have to tip.

The DSN has been converting its LNAs from Masers to High Electron Mobility Transistor (HEMT) amplifiers. These are solid state devices that arc cooled to only 12 K, resulting in a reduced cost for the cryogenic refrigerat or. At S-band, HEMTs have about the same noise performance as masers.

For this reason, we have already begun converting our S-band **1.NAs.**

Although X-band HEMT LNAs have a slightly higher noise temperature than their maser counterparts, wc can take advantage of the beam waveguide environment to build cooling packages that cool not only the HEMT, but much of the feed horn and other front end microwave equipment as was done with the ULNA. The total package is expected to have noise performance that surpasses the current tipping masers.

Ka-band HEMT devices are also under development at JPL. Here, we have the additional problem of characterizing these devices at low temperatures and high frequency. Special technologies arc being developed for on-wafer characterizat ion [4],

5. Ncw **Receivers**

Since its beginning, the DSN has used binary phase shift keying (BPSK) as the predominant modulation type with deep space missions. Simple first order phase lock loops have been used up until this year.

This year, the DSN introduced a ncw generation of receivers based on technology developed in the research program. These receivers, called the Block V, are digital receivers that combine the demodulat ion of carrier, subcarrier, and symbols in an integrated design [5].

The Block V receivers also allow ncw DSN modulation types, including QPSK and fully suppressed carrier in BPSK.

Costas carrier tracking phase locked loops with sideband aiding are employed. Loop bandwidths and orders can bc controlled digitally to optimize performance as a function of time,

State of the art gallium arsenide (GaAs) microelectronic technology is used to implement the signal processing portions of the receivers.

In addition, the Block V receivers will reduce DSN costs. They arc much smaller devices than the older receivers, taking up less than 1/1 O the space. They also replace subcarrier and symbol demodulation units. Final ly, they provide functionality for arraying signals from multiple antennas (see Section 6.)

6. **Antenna Arraying**

It ı order to make the best usc of the DSN's antennas, sometimes the signals from a single spacecraft incident on several antennas must bc combined. This can happen when a customer requires more gain than can bc provided with a single 70m antenna, It could also bc the case that a customer would require the equivalent area of two 34m antennas, but that the 70m's arc required for another customer at the same time.

For these reasons, the DSN has been developing methods of arraying its antennas.

The first usc of antenna arraying for deep spacecraft communications was for Voyager 2's Uranus encounter. It was the primary mode used at Voyager's Neptune encounter.

Even before this, antenna arraying techniques were used to support ground-based science observations including the Goldstone Solar System Radar and Very 1.ong Baseline Inteferometry (VLBI.)

Up until now, the primary mode for antenna arraying in the DSN has been baseband arraying [6]. In the baseband arraying system, the carriers at each antenna arc demodulated. The baseband signals arc then combined at a central location. Baseband arraying has two disadvantages. First, it requires sufficient signal strength at each antenna for good carrier demodulation to occur. Second, once the carriers arc demodulated, any information they may have carried that could bc usefu I in the combining operation is lost.

New techniques have been developed within the research program that will perform better. These include full spectrum combining and complex symbol combining [7].

Either of these schemes will perform almost as well as ideal carrier arraying (perfect summation of signals) under nominal conditions. They are being implemented for the Galileo mission.

7. New Error Correcting Codes

One tool that is used to increase telemetry performance for deep space missions is error correcting coding. Through coding, redundancy is added to the raw bit stream transmitted by a spacecraft in such a way as to allow bits correctly received on the ground to help fix bits that arrive in error.

Figure 6 shows a steady evolution of codes used by the DSN for deep space missions. The horizontal axis is E_b/N_0, the energy required in each bit of information to achieve the indicated bit error rate performance. The mathematical limit for coded performance (the *Shannon* limit) is indicated on the Figure.

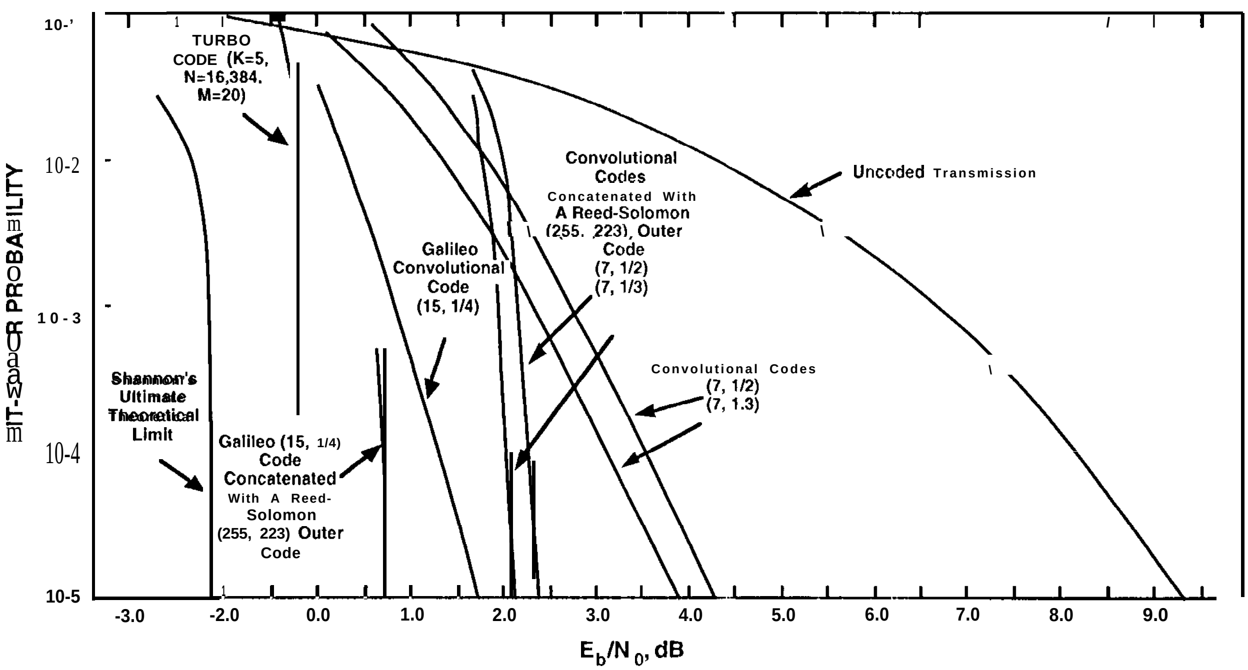

Figure 6.
Performance of various error correcting codes

The current coding system used by most missions consists of an inner (7, 1/2) convolutional code concatenated with a (255, 223) Reed-Solomon code.

The Galileo mission will use a more powerful code. The inner code will be a (14, 1/2) convolutional code. The outer code will be a variable redundancy Reed-Solomon code. Instead of each codeword being the same length, a set of four codewords will be grouped together into a code block. Each codeword will have a different amount of redundancy added, The most redundant words will tend to decode with the most reliability. The corrected bits from these words can then be used to aid in the correction of the other codewords.

The latest codes under development for the DSN are called *turbo codes* [8]. Turbo codes use concatenated convolutional encode]s to generate very powerful codes that (in some cases) are simpler to decode than similar performance conventional codes.

With the advent of very powerful, small computers, much decoding can now be performed in software. All the decoding for the Galileo S-band mission will be accomplishcd in software. Turbo codes, with their promise of simpler decoding algorithms, may lend themselves to a software implementation - even at more typical deep space data rates.

8. Data Compression

The performance of the telemetry link can be increased by reducing the amount of bits that arc actually transmitted to represent the required information. Data compression is the technology used to reduce the redundancy in the source data. Although data compression was used in deep space missions as far back as Voyager 2 [9], and more recently planned for Galileo before the HGA problem [10], future missions will use the technique to a much greater extent.

Most of the research performed by the DSN in data compression is related to compressing images. This is because image data (both monochromatic and multi-spectral) represents the bulk of data transmitted from deep space. Sonic effort has been placed into other high bandwidth data types such as that from seismographs [11].

Special adaptations of the Joint Photographic Expert Group (JPEG) image compression standard have been created for usc on deep space missions [12]. These produce very high fidelity results for planetary images at 10:1 compression ratios (an equivalent 10 dB performance gain) and good results up to 40:1,

Ncw techniques under investigation include using code division multiple access (CDMA) techniques to communicate with man y spacecraft in orbit around a planet (c, g. Mars) [13] - since all the spacecraft would be in the beamwidth of a single 34m antenna. This could reduce costs substantially since a single antenna could be used to support all these spacecraft.

9. Ionic Clocks

Deep space missions arc navigated primarily from observation of their radio signals. The three main t ypcs of radio metric measurements used are Doppler (frequency shift in the signal due to relative acceleration of the spacecraft), range (round trip travel time for the signal), and Very Long Baseline Interferometry (precise measurement of the angle the signal makes with the Earth made using two ground antennas.) All of these require very precise and accurate measurements of time. Radio science (using perturbations in the signal to infer information about something in the signals path - e.g. a planetary atmosphere) puts an even greater strain on time measurement. For these. reasons, the DSN has always used state of the art frequency standards,

The current frequency standard in the DSN is the Hydrogen maser. This atomic clock uscs transition states in the Hydrogen atom to lock a microwave reference signal. The Hydrogen maser can produce frequencies that arc good to a part in 10^{15} at averaging intervals of 1,000 seconds (typical of round trip light time.s to planetary spacecraft.)

A ncw technology, the Linear Ion Trap (LIT) [14] can surpass the Hydrogen maser in performance, and hence enable gravitational wave detection experiments that will be conducted with the DSN in the year 2000. A drawi ng of the physics package of the LIT is shown in Figure 7. The LIT uscs Mercury ions rather than Hydrogen atoms. Ions, being charged particles, can be confined in a given space using small electric fields. Atoms, on the other hand, require bulky magnets for confinement, By confining the ions to a linear region in space - rather than in a point as is done for atoms - more ions are confined. This increases the signal to noise ratio of the system, providing an enhance measurement.

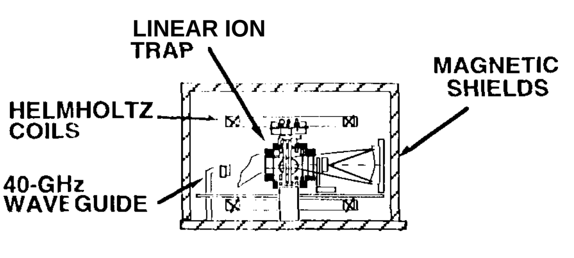

Figure 7
Physics package for the linear ion trap (LIT)

Two prototype LIT units have been built, They have demonstrated a frequency stability of about 5 parts in 1016 for 1,000 seconds.

10. Reengineering

Dividing the total 1994 DSN budget (including planning, operations, engineering, and research) by the total number of tracking hours provided leads to a cost per tracking hour of about $3,000. If the total annual DSN budget were to remain constant through 1999, the cost per tracking hour must decrease to about $1,800 to accommodate the increase in capacity. In reality, the DSN budget will not remain constant over this period, but will decrease. All of this leads to the conclusion that the DSN must become twice as efficient by 1999 as it was in 1994. This must also happen at a time when the DSN will be adopting many new technologies, leading to a substantial implementation near-term investment. This degree of progress is not likely to be achieved through the continuous improvement programs already in place, but rather will require a more radical rethinking of the basic processes used in operating the network.

Since there needs to be a fundamental change in the way DSN operations functions, we decided to try using *reengineering*. Reengineering is a technique for creating substantial improvements in performance. The formal definition of reengineering (according to Hammer and Champy [15]) is

> *the fundamental rethinking and radical redesign of business processes to achieve dramatic improvements in critical measures of performance.*

Since reengineering was new to JPL, and since it was being used with great success in many American companies at the time, we decided to follow Hammer and Champy's methodology closely. In this way we would achieve two objectives: obtain the required gains in DSN operations efficiency and determine the applicability of reengineering to NASA and the DSN.

A full account of the reengineering work appears in [16]. By far, the most important change in DSN operations will be the reengineered Data Capture process.

Data Capture is the process in which all real time communications and tracking of customer spacecraft (i.e. *activities*) takes place. The old DSN data capture system is characterized by Figure 8

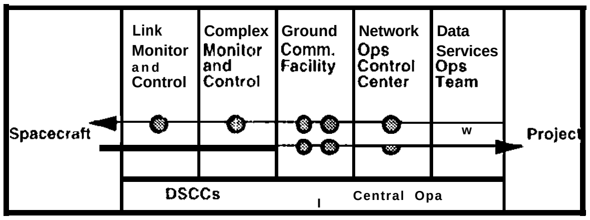

Figure 8
The old DSN data capture system

The circles represent control points in the system. Notice that the current system is divided into a series of separate facilities. Each of these facilities has its own people, tools, and procedures. Each one has to work in order for Data Capture to succeed in delivering customer services.

Historically, it was beneficial to build Data Capture in this way. When the DSN was new, there were many complex engineering challenges to overcome. Dividing the problem up into simpler tasks resulted in a manageable set of goals to accomplish.

There are, however, several problems with this facilities-oriented approach. First, there is a tendency to duplicate functions in each facility. Examples of this duplication include the customer interface function, report generation, and certain kinds of tool development.

A second problem is that each of the interfaces between these facilities must be managed carefully to reduce errors. This is particularly difficult as adjacent facilities on the diagram can be in distinct management organizations.

Data Capture has been reengineered by reducing the number of facilities to just two and redefining all the jobs in the system. The result is shown in Figure 9.

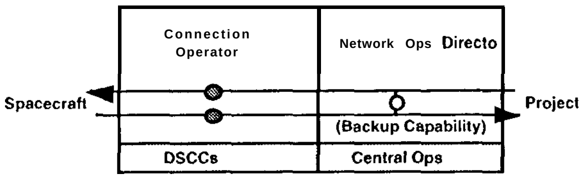

Figure 9.
Reengineered data capture system

In the new Data Capture system, a single person (called a Connection Operator) will be responsible for the end-to-end process during any real time activity. During any activity, the Connection Operator provides the primary interface with the customer. In some sense, the Connection Operator can be thought of as working for the customer.

At some central location, a single person, the Network Operations Director (NOD) will be responsible for the execution of Data Capture for all customers. The NOD will have similar tools to those used be the Connection Operators and can assist with the handling of exceptions that may occur. Exception Handlers will work for the NOD and will provide additional expertise to assist the Connect ion Operators when trouble arises. The NOD is responsible to the process owner of Data Capture.

A second area that has been reengineered is the process by which support data (i.e. antenna pointing instructions, predicted performance, DSN equipment configuration, and customer sequences of events) is prepared for activities. The is called the Activity Plan process.

The reengineered activity plan process has two major improvements, First, all support data is generated on the fly from latest-avai lable data residing in a central data management system. This replaces a batch system that led to the generation of multiple sets of data in advance for contingent conditions.

The second improvement is a move from event-oriented planning on the part of our customers to service-oriented planning. Before, the customer had to have a in-depth understanding of particular sets of DSN equipment to allow an activity to proceed, In the future, customers will request services from a DSN standard service catalogue. The service request will be site-independent. Just before an activity commences, the request will be translated into a series of automation scripts for use by the actual equipment in the DSN.

These reengineering improvements will allow the DSN to meet its operations efficiency goals in the year 2000.

11. Galileo as a Sign of the Future

The Galileo mission to Jupiter experienced a major setback when its X-band High Gain Antenna (HGA) failed to deploy in 1991, When it became clear that the HGA could not be freed, the DSN began working with the Galileo project to create a viable mission that could be flown entirely on the S-band Low Gain Antenna (LGA). Without the HGA, the Galileo signal is degraded by some 40 dB.

The resulting Galileo S-band mission represents (except for the fact it is at S-band) a glimpse into the DSN of the next century. This is because, in order to develop a Galileo S-band mission with a meaningful amount of science return, all new technologies under development in the DSN were called into action. In fact, the Galileo S-band system will represent the first use of many new communications technologies, Many of these new developments will become routine after Galileo.

The full blown S-band mission as described here, begins with Galileo's orbital tour in the spring of 1996.

The DSN will routinely array its large antennas to maximize signal collection for Galileo. In Australia, which has the best view of the Galileo spacecraft, as many as four antennas will be arrayed on a regular basis. The arraying techniques take advantage of the complete spectrum of the Galileo signal (as passed through the LNAs.)

Galileo will be the first DSN deep space mission to used fully suppressed carrier tracking. The DSN's newest receivers, the Block V digital receivers, will be used.

Galileo will optimize its telemetry link by changing data rates as many as eight times each day in order to compensate for the increased atmospheric losses and low ground antenna elevations. The ncw DSN ground system will track through these rate changes, looking backward in time at buffered data as needed so as not to lose a single bit.

An optimized S-band feed-LNA system (called the *ultrcone*) will be used on the DSN'S 70m antenna in Australia - the key antenna for Galileo. Many of the same techniques that arc used to develop optimized LNA performance at higher frequencies were used in its design.

New, more powerful error correcting codes are to be used as described in the Section 7.

The improvements listed so far represent about a 10 dB improvement in Galileo's link performance.

A second 10 dB comes from the judicious use of data compression. All images will be compressed. Ratios between 10:1 and 20:1 will be common in the mission. Images that will be used to provide data for navigating the spacecraft will even be compressed further.

Together, the use of new technology has resulted in a predicted 20 dB improvement in Galileo's telemetry link. The improvements represent a very small investment when compared to the funds expended on the mission. in addition, many of the improvements will be applicable to future deep space missions using the DSN.

With these improvements, and an equally substantial effort in spacecraft planning and software development, the Galileo project est i mates it can achieve 70% of the science objectives originally planned for the mission.

12. Conclusions

As indicated in the beginning of this paper, the DSN must face significant challenges to meet both the performance and cost requirements imposed by the NASA environment. However, the cadre of technologies and operational changes available to the DSN should allow us to meet these challenges and retain our status as a premier facility for deep space communications, tracking, and science.

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